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INTEGRATION OF AN ISOTOPE BRAYTON POWER SYSTEM WITH A LIFE SUPPORT SYSTEM

by James N. Deyo, John L. Klann, and Raymond S. Bilski
Lewis Research Center
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

An analytical study was conducted to determine the feasibility of using an isotope Brayton power system to supply both the electrical and thermal needs of an integrated life support system. The study was conducted as a joint effort by staff members of the NASA-Lewis and NASA-Langley Research Centers. Emphasis was placed on studying the steady-state and transient interactions that would result from thermal integration of the two systems.

Results of the study show that thermal integration can be accomplished most flexibly by extracting heat in the Brayton power system's waste heat loop through the use of an auxiliary liquid-to-liquid heat exchanger. Thermal transient effects on both systems are within operating tolerances. However, to provide the life-support-system process heating temperature requirement will necessitate operating the power system compressor inlet temperature about 40° F above the existing design point of 80° F, thereby reducing the calculated power system conversion efficiency from 0.29 to 0.27.

Hardware modifications to permit integration were examined and found to be minor. Both systems can be made electrically compatible by the addition of a frequency converter.

Introduction

For the long duration manned space missions now being planned by NASA, regenerative life support systems and multi-kilowatt electric power generating systems will be needed. NASA-Langley Research Center has been engaged in advanced technology to develop long-life regenerative life support systems suitable for such missions. Similarly, NASA-Lewis Research Center has been engaged in advanced technology to develop long-life multi-kilowatt space electric power generating systems.

The Langley-integrated life support system (ILSS, Ref. 1) and the Lewis-Brayton power system (BPS, Refs. 2 to 4), currently being evaluated in separate ground tests, contain concepts and hardware which could be used for these advanced missions.

This report summarizes the method and results of a Lewis-Langley study conducted to determine the feasibility of mating the ILSS and BPS thermally and electrically for integrated operation. The existing BPS and ILSS are described. Potential methods of integration were examined by means of steady-state (Ref. 11) and transient (Ref. 12) computer analyses. Results of these analyses are summarized, and required hardware changes for the selected integration method are described.

This study was based upon two existing systems. Analytically mating two existing systems and using experimental data was beneficial in establishing confidence in the accuracy of the results. Factors such as thermal capacitance of components, interface requirements, and integration penalties could be more clearly evaluated than if the two systems had been only concepts.

Experimental performance data for the ILSS and expected performance data for the BPS were used during the study. The BPS was being installed for testing in the NASA-Space Power Facility, Sandusky, Ohio, at the time of this study. Testing of the BPS is now in progress and performance results covering 2042 hours of operation are reported in Refs. 3 and 4.

Systems Description

Life Support System

The Langley integrated life support system (Ref. 1) is housed in a test chamber approximately 18 feet in diameter by 18 feet long. The chamber is divided into two levels with quarters for a crew of four men on the upper level and the life support subsystems arranged in a flight-type fashion mainly on the lower level. Thermal and electrical power to the life-support subsystems is provided by test support equipment outside of the test chamber. The ILSS is designed to support four men for one year with a resupply of food every 90 days. It was built to evaluate regenerative life support concepts.

Major subsystems of the ILSS are: thermal control, atmospheric control, water management, waste management, personal hygiene, food management, and instrumentation and control.

Figure 1 shows the three primary thermal control circuits in the ILSS. The process heat and primary cooling circuits use Dow-Corning 331 and Propylene Glycol liquid, respectively. Thermal interfacing with the Brayton power system occurs at the life support heat source in the process heat circuit.

A schematic of the process heat circuit flow distribution and thermal requirements is shown in Fig. 2. The average process heat load is 6.2 kWt. The function of the fluid pumping and heating unit, shown in Fig. 2, would be replaced by the BPS and a fluid circulating pump in an actual integration. The actual process heat load varies in a cyclic nature from 4.4 to 7.9 kWt over a period of 40.2 minutes (Fig. 3).

Electrically, the ILSS uses 120/208 Vac 3-phase 400-hertz and 28-volt-dc power. The average total power requirement is 5.2 kilowatts with peaks to 5.8 kilowatts. The ac and dc load profiles are shown in Fig. 4.

Brayton Power System

The Brayton power system consists of a heat source, power conversion system (engine), and heat rejection system as shown schematically in Fig. 5. Working gas, a helium-xenon mixture at the molecular weight of krypton, is heated in the heat-source heat exchanger. It then passes through the turbine, recuperator, waste heat exchanger, compressor, recuperator and back to the heat source. Within the engine, the electrical power producing component is the Brayton Rotating Unit (BRU). It consists of a turbine, alternator, and compressor mounted on a common shaft which is supported by gas lubricated journal and thrust bearings. The alternator produces 120/208 volts, 3-phase electric power at a frequency of 1200 hertz. The power output of the engine can be set within the range of 2 to 15 kilowatts by varying the inventory of working gas within the system. Variations in the user's load, below the selected power output of the engine, are accommodated by using an electrical speed control system. This system uses a parasitic load resistor to absorb excess power. Electrical housekeeping needs, in addition to the speed control, includes power to run the heat rejection system pump, operate the engine control system, and charge the engine batteries. The electrical system supplying these functions is shown in Fig. 6.

Waste Brayton-cycle heat is rejected to a liquid cooling loop through the gas-to-liquid waste heat exchanger (Fig. 5). Liquid cooling is also provided to the alternator in the BRU and through a series of cold plates. Electrical system components are mounted on these cold plates. Two redundant liquid cooling loops are provided. However, during operation, circulation is required in only one liquid loop. A silicone liquid (DC-200) is used. Present ground testing uses a radiator-simulator heat exchanger in place of a space radiator.

More detailed descriptions of the components of the Brayton power system are given in Refs. 5 through 9.

Study Assumptions

For the purpose of the study, the following assumptions and ground rules were established.

ILSS Assumptions

(1) Use the experimentally determined values for electrical and thermal requirements.

(2) Assume all existing subsystems and components (i.e., no product improvements).

(3) All electrical and thermal power will be provided by the Brayton power system.

(4) Thermal cooling of the ILSS will be provided by a space radiator (or radiator simulator) separate from the Brayton radiator.

Brayton Power System Assumptions

(1) Assume a long-lived isotope heat source. The source heat exchanger and isotope array will be sized to provide working gas at 1600° F to the turbine inlet.

(2) Working gas will be a mixture of helium and xenon having a molecular weight of 83.8.

(3) Assume only the electrical and thermal loads of the ILSS plus a 1.5 kilowatt electric margin for establishing the net power output of the Brayton engine.

(4) The method of heat transfer to the ILSS should be consistent with minimizing the size of the isotope heat source.

Interface and Integration Assumptions

(1) Thermal power will be transferred to the ILSS from the BPS by using an auxiliary heat exchanger. A 50° F temperature drop between fluids will be assumed on the hot end of the heat exchanger.[1]

(2) An efficiency of 80 percent will be assumed for equipment to convert the 1200 Hz BPS power to 400 Hz and dc for the ILSS.

(3) Use of 1200 Hz power directly in the ILSS will be investigated.

(4) The study should seek to minimize hardware changes to both systems.

Discussion

The power system was examined for possible methods of supplying the ILSS thermal requirements. Figure 7 presents the two methods investigated for removing waste power system heat; namely, either a gas-to-liquid or liquid-to-liquid auxiliary heat exchanger. In concept either of these heat exchangers would replace the heat exchanger portion of the ILSS fluid heating and pumping unit shown in Fig. 2.

To provide the ILSS average power requirement of 5.2 kWe, the BPS was assumed to be rated for 9.4 kWe at the alternator terminals.

Distribution to the integrated systems would be:

BPS alternator gross output, kWe	9.4
BPS internal housekeeping power, kWe	1.4
BPS margin, kWe	1.5
Gross average power available to ILSS, kWe	6.5
Power conditioning loss at 0.80, kWe	1.3
Net average power available to ILSS, kWe	5.2

The BPS thermal conditions shown in Fig. 7 are for a gross alternator power output of 9.4 kWe. At this condition, 16.6 kWt is rejected into the waste heat exchanger. Although there was enough waste power for ILSS needs, it was at a lower temperature than needed by the existing ILSS (342° F waste heat exchanger gas inlet temperature, Fig. 7; compared to 425° F required at the same point to deliver fluid to the ILSS at the required 375° F, Fig. 2, allowing for the 50° F assumed auxiliary heat exchanger temperature drop).

The Langley staff conducted bench tests on components of the ILSS process heat circuit to examine changing the heat transport fluid. Water, rather than the original Dow-Corning 331 silicone fluid, was found to be acceptable. The use of water reduced the required inlet temperature from 375° F to 300° F while maintaining the original flow rate. Using the assumed 50° F Δt across an auxiliary heat exchanger resulted in a required Brayton power system supply temperature of 350° F. These changes were adopted for the study as a reasonable compromise to make the systems more compatible.

Steady-State Integration Analysis

By using existing Brayton digital computer programs, two steady-state thermal integration analyses were performed. These programs simulate the Brayton power system configuration of Ref. 2 and are based on measured component data. The programs are described in Ref. 10.

Higher BPS temperature. - The first analysis parametrically investigated two methods to raise the power system waste heat temperature to the required 350° F; namely, raising the compressor inlet temperature above design along with lowering liquid coolant mass flow rates, or reducing the recuperator heat transfer effectiveness.

Figure 8 shows the extent to which the compressor inlet temperature must be raised above the design point of 80° F to achieve a 350° F inlet temperature to either auxiliary heat exchanger concept. Use of an auxiliary liquid-to-liquid heat exchanger will require operating the compressor inlet nearly 40° F above design, while the use of an auxiliary gas-to-liquid heat exchanger will require about a 10° F increase. The difference is due to the higher inlet temperature available to a gas-to-liquid heat exchanger (Fig. 7).

Figure 9 examines the parametric effects of compressor inlet temperature on other power system operating conditions for both auxiliary heat exchangers. In each case, changes in power system conditions are greater when operating with a liquid-to-liquid auxiliary heat exchanger. The more important effects being a 0.02 drop in conversion efficiency coupled with a required 2 kilowatt increase in gas thermal input.

Reducing recuperator heat transfer effectiveness affects operating conditions as shown in Fig. 10. Three values of effectiveness were evaluated with 0.94 being the effectiveness of the present recuperator. Cross plots of constant coolant temperature on the conversion efficiency curve show that while reducing effectiveness from 0.94 to 0.90 has a significant effect on compressor inlet temperature it has little effect on conversion efficiency. Since there is no gain in conversion efficiency to justify the change in hardware that would be required to lower recuperator effectiveness, this approach was discarded in favor of simply operating the compressor inlet at a higher temperature.

Power system excursions. - The second analysis examined excursions in a simulated space version of the BPS caused by changes in the ILSS heat load. BPS operating conditions were first established assuming the ILSS operating at its average 6 kWt heat load. Changes to the BPS operating conditions were then investigated by assuming the average steady state ILSS heat load had changed from 6 kWt to first 0 kWt, then 4 kWt, and finally 8 kWt. The computer program was modified to permit the assumption of either gas-to-liquid or liquid-to-liquid heat removal from the BPS.

Figure 11 presents power system excursion limits when a liquid-to-liquid auxiliary heat exchanger is assumed. All power system temperature excursions would be less than ±20° F, for variations from 4 to 8 kWt, about an average 6 kWt ILSS load. Gross alternator power output would vary less than ±0.5 percent. The dashed portion of the curves from 0 to 4 kWt represents power system excursions if the ILSS heat load were removed. Turbine inlet temperature shows the greatest change increasing 40° F. In a real application the selection of power system operating conditions might be altered somewhat to limit the turbine inlet temperature excursion from operating above design (Ref. 11). For this study, the conditions chosen served to demonstrate the parametric effects that would be present in a real integration.

In Fig. 12 power system excursion limits are presented when a gas-to-liquid auxiliary heat exchanger is assumed. The results are very similar to those presented in Fig. 11. Maximum variations were slightly greater being about ±25° F, due to the ±2 kWt change in average ILSS heat load.

Steady state results. - Several results were reached regarding the ability of the Brayton Power System to supply ILSS needs:

(1) ILSS electrical requirements are well within the power range of the Brayton Power System. In addition, setting the alternator gross power output to satisfy the ILSS electrically, results in sufficient power system waste heat being available to satisfy the ILSS thermal power requirements.

[1]Alternate means of transferring thermal power to the ILSS from the BPS were considered early in the study. These alternate methods included using electric heaters powered from the Brayton alternator, transferring heat directly from the isotope package to the ILSS, and circulating the Brayton cooling fluid directly through the ILSS process heat circuit. Each of these options were found to be either less efficient (required a larger isotope heat source) and/or had potential safety and/or reliability problems associated with them. Therefore, these methods were not investigated further.

(2) Since the ILSS requires heat at 300° F, some off-design operation of the power system will be required.

(3) Reducing recuperator effectiveness to raise heat rejection temperatures in the power system offers no real advantage over increasing compressor inlet temperature.

(4) Use of a gas-to-liquid auxiliary heat exchanger would require only about a 10° F increase in compressor inlet temperature and cause about a 0.01 lower conversion efficiency. Installation would require extensive hardware changes to the present power system recuperator and waste heat exchanger which are combined to form a single unit.

(5) Use of a liquid-to-liquid auxiliary heat exchanger would require about a 40° F increase in compressor inlet temperature and cause a 0.02 reduction in power system conversion efficiency. Installation would be extremely flexible since it would be inserted into the piping of the power system heat rejection system.

(6) The limits of power system excursions when the ILSS heat load is varied are reasonable and within operating tolerances of the power system.

From these results it was concluded that using a liquid-to-liquid auxiliary heat exchanger best satisfied the guidelines established for the study. The liquid-to-liquid heat exchanger offered the most flexibility, and was felt to be justified in spite of an additional one point drop in conversion efficiency. Details and additional information concerning the steady-state analyses may be found in Ref. 11.

Transient Analysis

An analog computer simulation of the power system heat rejection loop, including a conceptual auxiliary liquid-to-liquid heat exchanger core, was developed. This was coupled to an existing analog simulation of the Brayton gas loop described in Refs. 12 and 13, respectively. The conceptual liquid-to-liquid auxiliary heat exchanger core was designed and is shown in Fig. 13.

Steady state effects from the analog computer simulation of varying the ILSS heat load on power system operating conditions and ILSS water supply temperature are shown in Fig. 14. ILSS water inlet temperature decreases with increasing heat load. Compressor inlet and turbine inlet temperatures follow the same trend but do not cause a change in power system conversion efficiency or output since the Δt between compressor and turbine is relatively constant. These results compare closely with the steady state digital analyses.

To determine transient variations in ILSS process water temperature, power system output, and power system compressor inlet temperature during integrated operation, three consecutive ILSS thermal load cycles were applied to the analog simulation.

Results were identical and are presented for one cycle in Fig. 15. ILSS process water temperature varied ±17° F about the 300° F average value. Power system compressor inlet temperature varied between 106° and 118° F. Electrical power output remained nearly constant. These variations are within acceptable operating limits for both systems.

To determine the effect of starting the ILSS on the Brayton Power System, a thermal load of nearly twice the rate encountered during normal operation (Fig. 3), was investigated using the analog simulation. Startup assumptions were:

(1) The Brayton Power System is started and allowed to stabilize at its operating condition.

(2) The ILSS process heat water flow is adjusted to its design value and the water temperature allowed to stabilize with no heat being withdrawn by the life support subsystems.

(3) The ILSS equipment is turned on creating an assumed thermal load which increases uniformly from 0 to 8 kWt in 100 seconds. The thermal load then is assumed to remain constant at 8 kWt until all transient effects are completed.

Figure 16 shows the results of this investigation. Effects on both systems were well within operating limits.

The transient analysis confirmed that an auxiliary liquid-to-liquid heat exchanger could be used to supply heat to the ILSS. Coupling between the two systems is weak and both should operate within acceptable limits during startup and normal operation. Additional information concerning the transient study is presented in Ref. 12.

Hardware Changes

If an actual integration of the present life support and power system hardware were to be made, the study has shown that modest changes would be required. The Integrated Life Support System process heat circuit would be converted to operation with water. This would involve replacing the Dow-Corning 331 silicone heat transport fluid with water and converting the carbon dioxide concentrator and water recovery unit heat exchangers to water operation.

An auxiliary liquid-to-liquid heat exchanger would have to be designed and fabricated. The redundancy of the Brayton heat rejection loop would have to be considered in the heat exchanger design and installation, so that the ILSS thermal needs could be furnished from either Brayton cooling loop. The power system heat rejection system piping would be easily interrupted to accept the auxiliary heat exchanger at a point immediately downstream of the liquid outlet of the waste heat exchanger.

A power converter would be required to convert the Brayton 1200 hertz electrical output to 400 hertz and dc for use with the ILSS subsystems. During the study, the Langley staff investigated the possible use of 1200 hertz power directly in the ILSS. It was concluded that it would be feasible for certain lighting, electrical heating, and motor applications. However, to incorporate 1200 hertz power in the present ILSS test chamber would require procurement and installation of suitable 1200 hertz components. The consideration of specific techniques of power conversion was not part of this study.

Conclusions

The results of the study indicate that it is feasible to use the 2 to 15 kWe Isotope Brayton Power System to supply both the electrical and thermal needs of the Langley Integrated Life Support System. Moreover, the integration can be accomplished without major modifications to either system. Steady state and transient interactions between the two systems are within the operating limits. Electrical integration required only the addition of a power converter to adapt the 1200 hertz output of the power system to the 400 hertz and dc power required by the life support system. Thermal integration can be performed most flexibly by installing an auxiliary liquid-to-liquid heat exchanger in the Brayton heat rejection loop. This approach results in a power system conversion efficiency about 0.01 lower than would be expected if a gas-to-liquid auxiliary heat exchanger were assumed between the recuperator and waste heat exchanger. However, major alterations to the recuperator-waste heat exchanger assembly would be required to incorporate the gas-to-liquid heat exchanger.

While sufficient power system waste heat is available to meet life support system needs, the power system must be operated at higher than design compressor inlet temperatures to meet ILSS temperature requirements. To minimize the amount of off-design power system operation required the ILSS thermal power temperature requirements can be lowered from 375° to 300° F by changing the heat transport fluid from Dow-Corning 331 to water. Raising the Brayton waste heat to 350° F (50° F Δt assumed across auxiliary heat exchanger) can be done by simply operating the compressor inlet temperature about 40° F above the design point of 80° F. Reducing recuperator effectiveness to accomplish the same result offered no advantage in power system conversion efficiency and would be difficult to do with the existing hardware. A tradeoff of weight against effectiveness in a final design of the auxiliary liquid-to-liquid heat exchanger might reduce the assumed 50° F Δt, which would allow a corresponding reduction in the amount of off-design compressor inlet temperature operation. Power system conversion efficiency would be improved as well.

The transient study also indicated that the Brayton power system and ILSS would remain within operating limits during the startup transient of the life support system.

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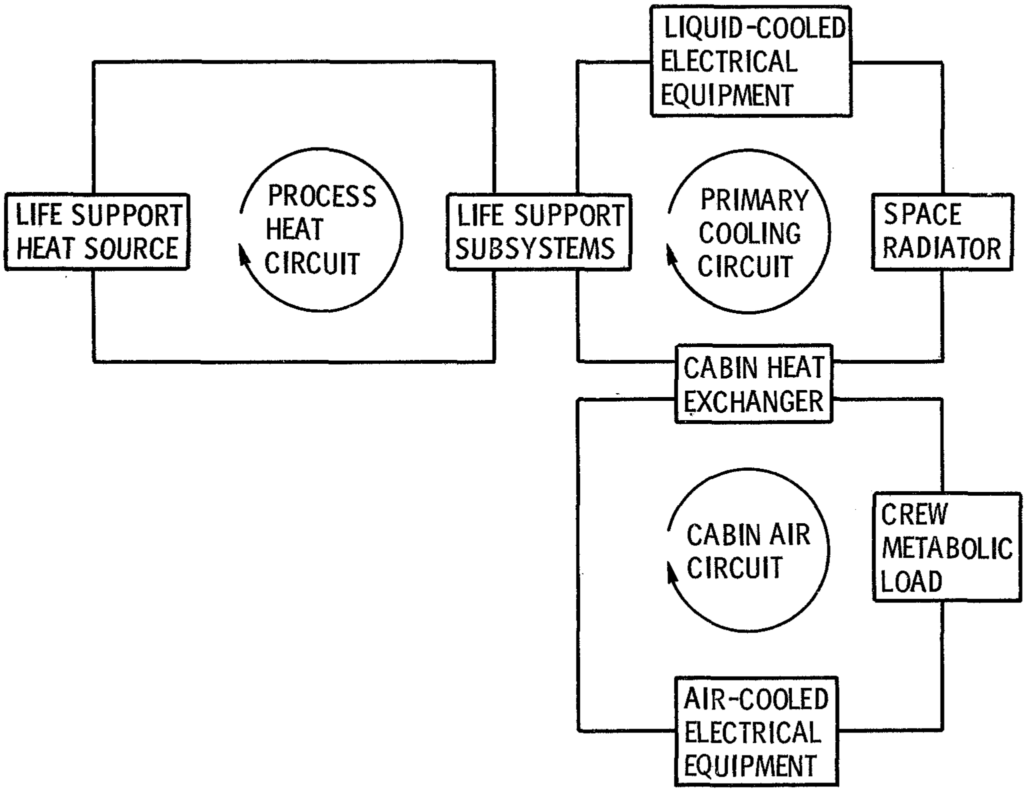
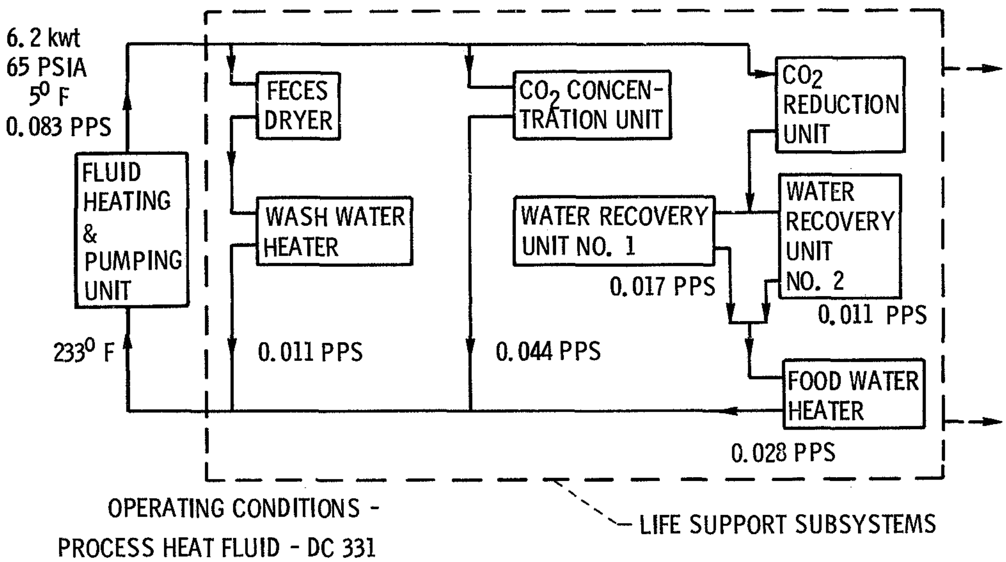


Figure 1. - ILSS thermal control circuits.



OPERATING CONDITIONS -
PROCESS HEAT FLUID - DC 331
SOURCE FLUID TEMP - 375° F
RETURN FLUID TEMP - 233° F
FLUID PRESSURE - 65 PSIA
FLUID FLOW RATE - 0.083 PPS
AVERAGE PROCESS HEAT LOAD - 6.2 kwt

Figure 2. - Process heat circuit flow distribution.

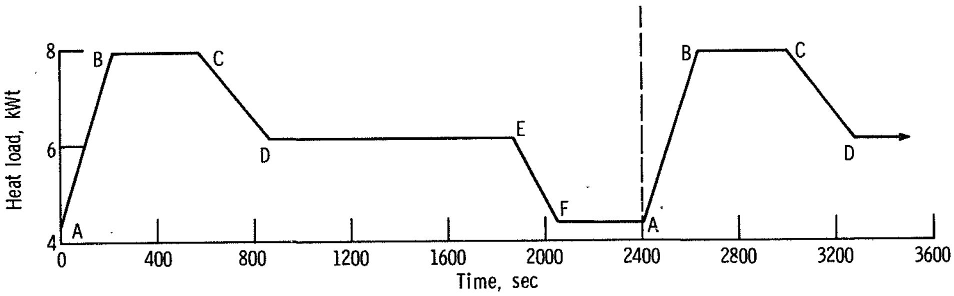


Figure 3. - Thermal power requirements of life-support system.

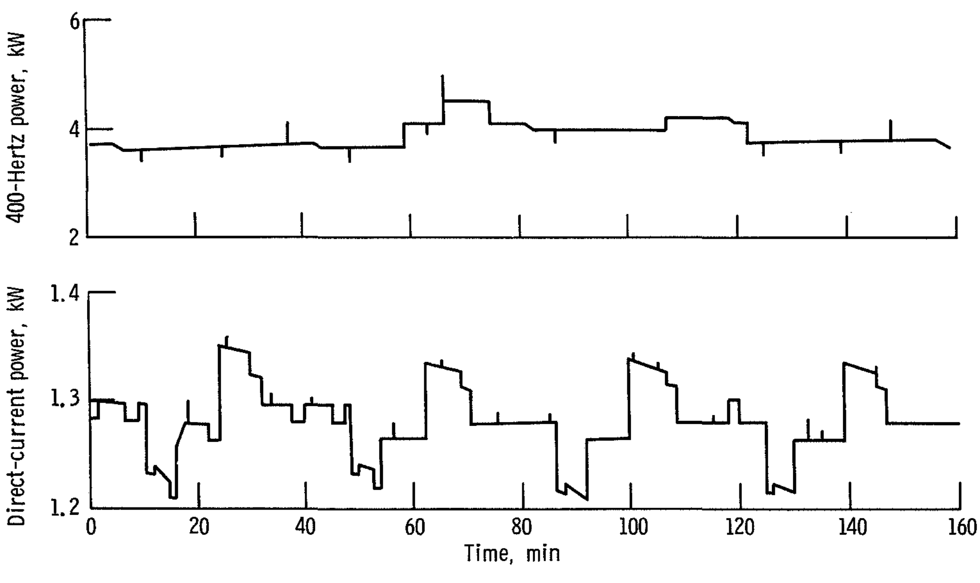


Figure 4. - Electrical requirements of life-support system.

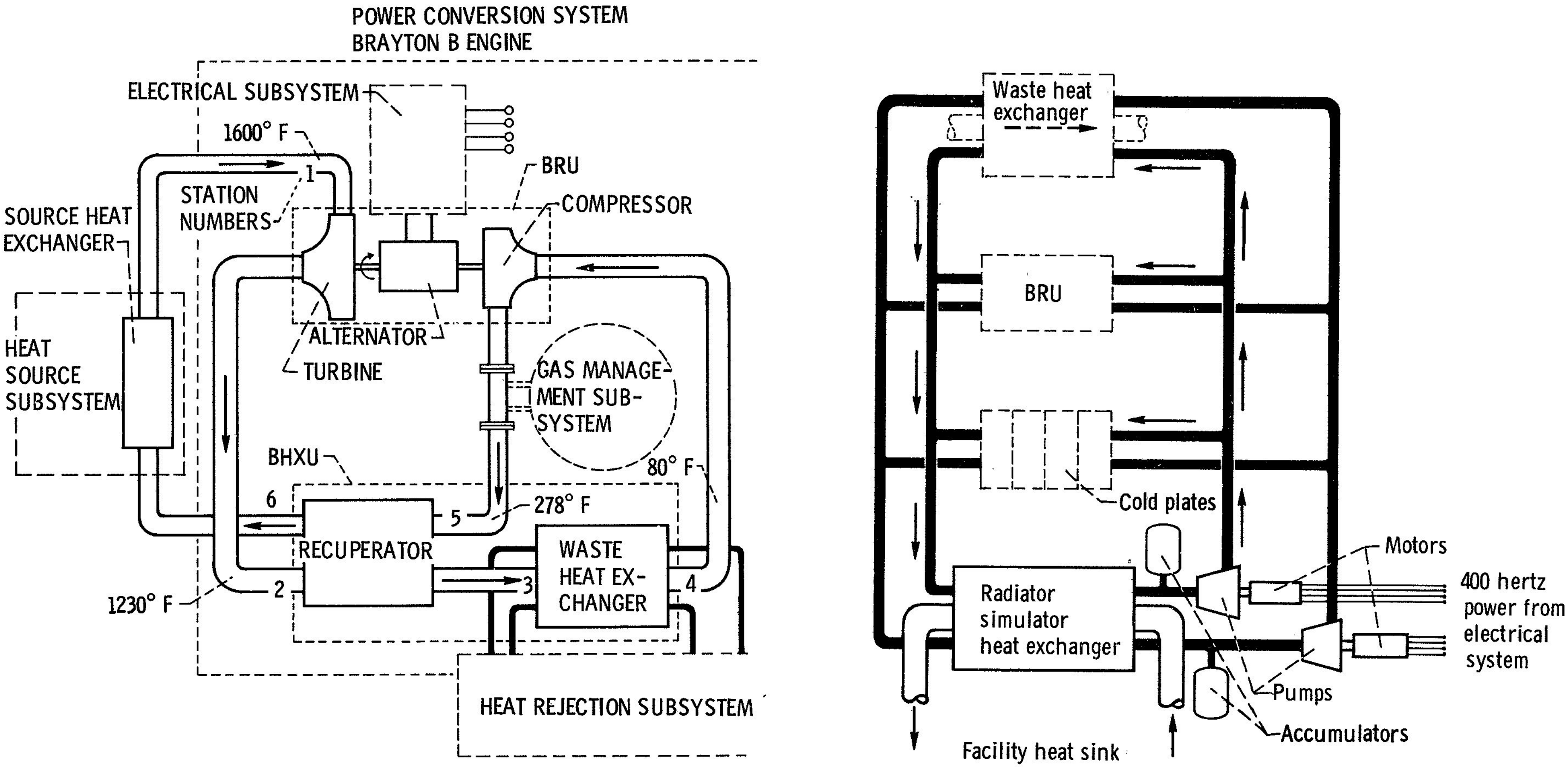


Figure 5. - Schematic diagram, Brayton power system and heat rejection subsystem.

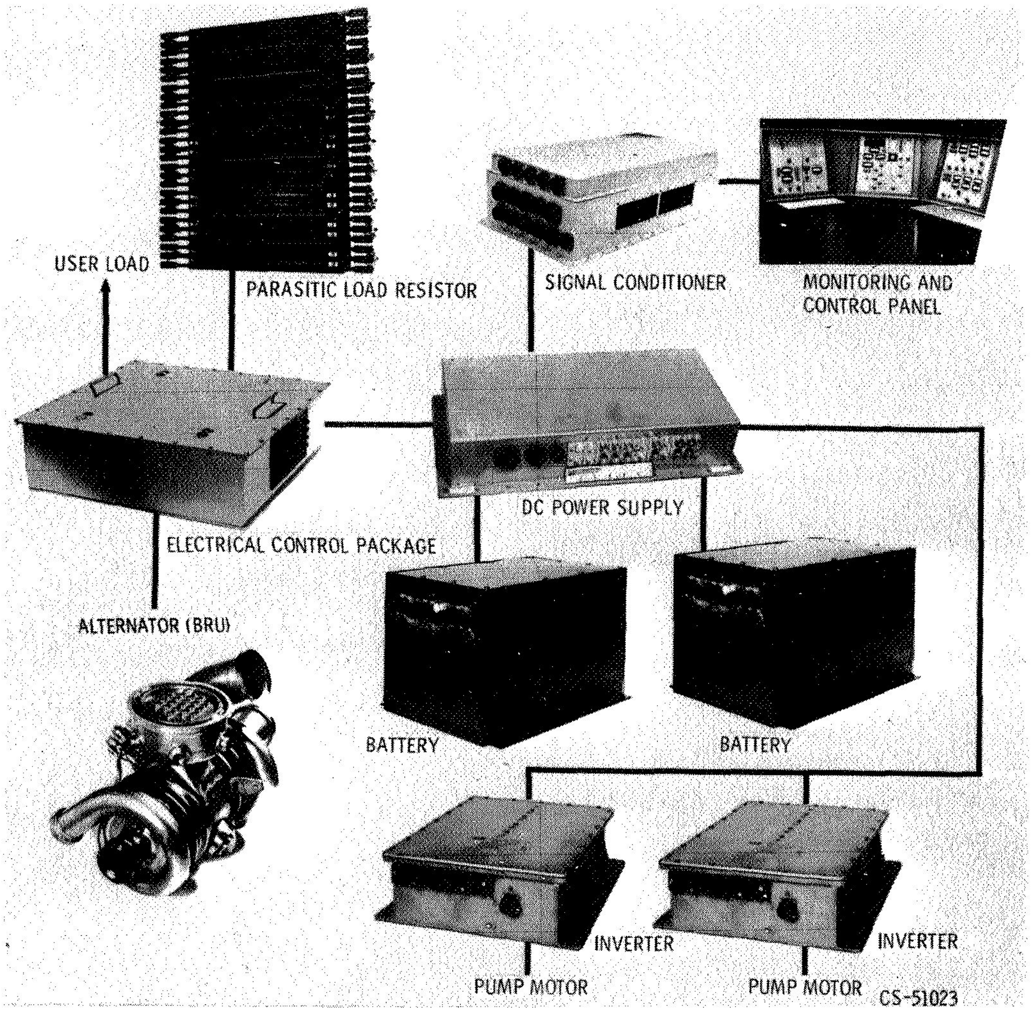


Figure 6. - Electrical system components.

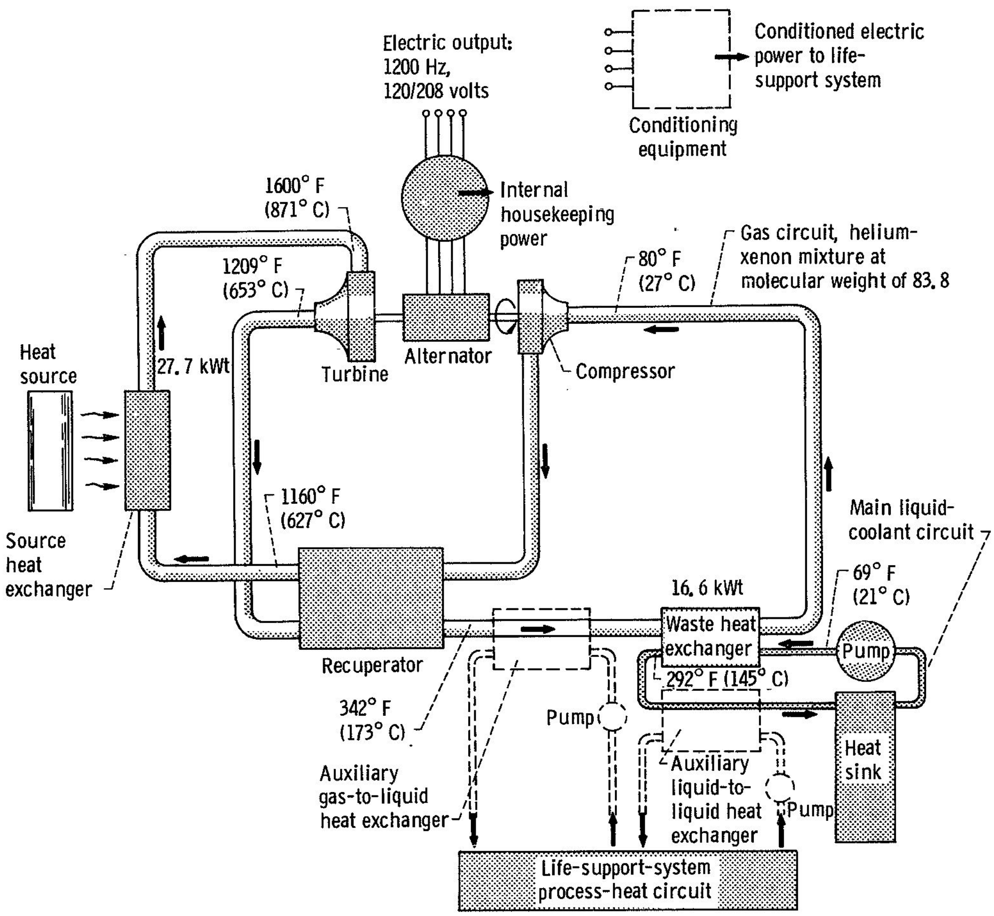


Figure 7. - Schematic diagram of Brayton power system showing life-support-system integration methods. Dashed lines denote new equipment required for electrical and thermal mating of systems.

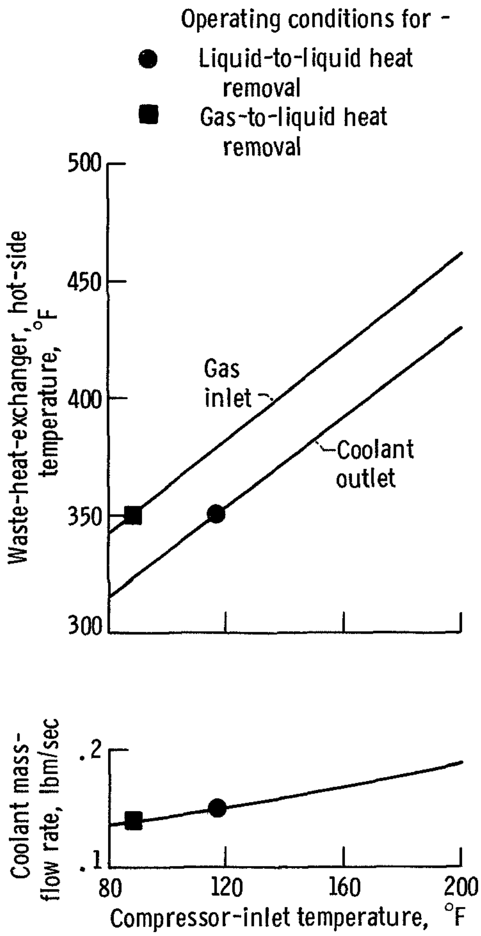


Figure 8. - Parametric effects of compressor-inlet temperature on heat-rejection temperatures. Gross alternator power, 9.4 kilowatts electric; turbine-inlet temperature, 1600° F; waste-heat-exchanger capacity-rate ratio, 1.0.

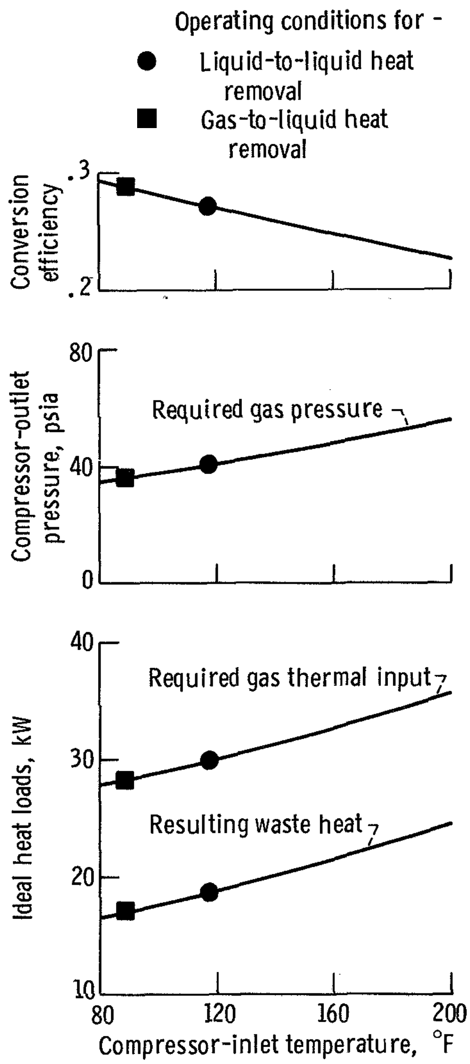


Figure 9. - Parametric effects of compressor-inlet temperature on operating conditions. Gross alternator power, 9.4 kilowatts electric; turbine-inlet temperature, 1600° F; waste-heat-exchanger capacity-rate ratio, 1.0.

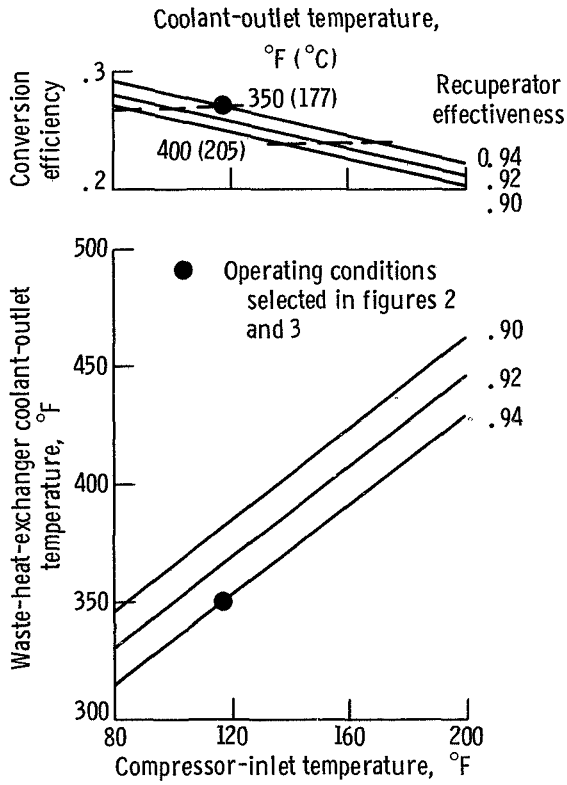


Figure 10. - Parametric effects of recuperator heat transfer on operating conditions. Gross alternator power, 9.4 kilowatts electric; turbine-inlet temperature, 1600° F; waste-heat-exchanger capacity-rate ratio, 1.0.

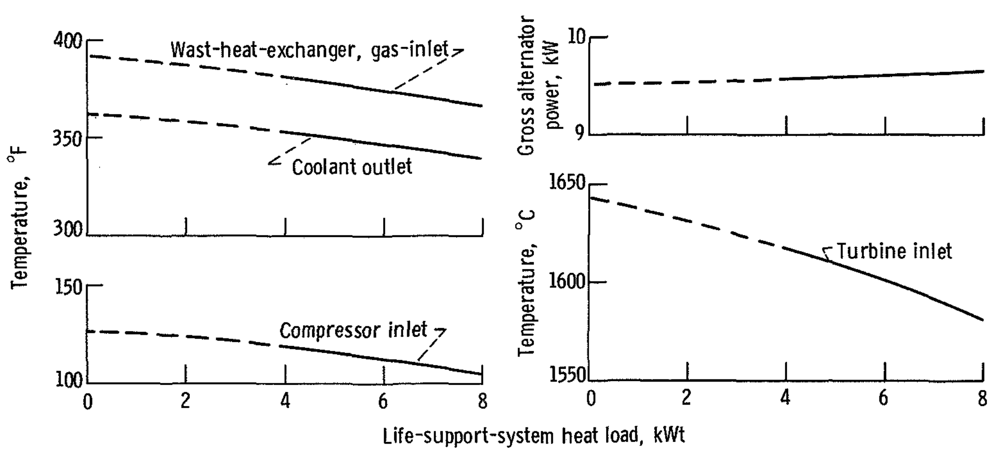


Figure 11. - Steady-state effects of coolant heat removal on fixed-power-system operating conditions. Ideal gas-thermal-input, 30 kilowatts thermal; prime radiator area, 260 square feet; coolant mass-flow rate, 0.15 pound mass per second; working-gas inventory, 1.035 pounds mass.

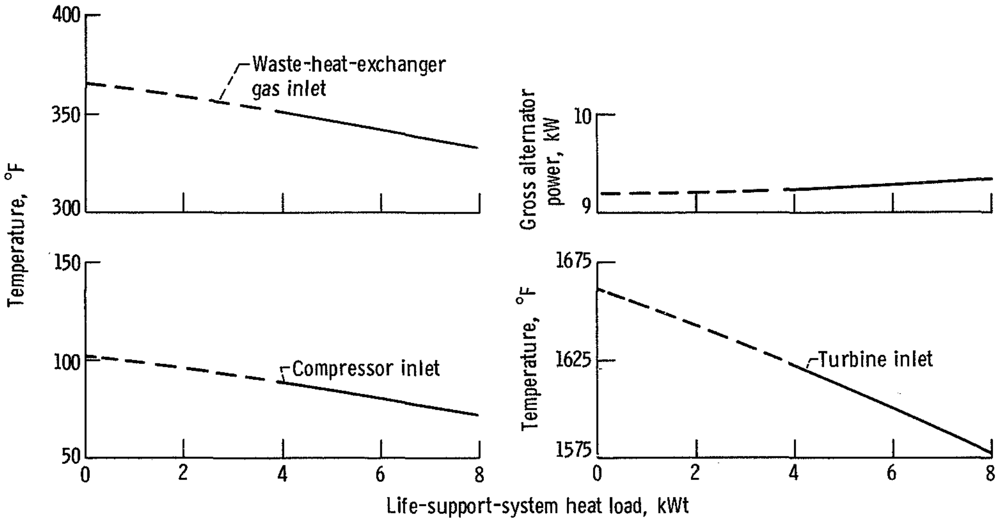


Figure 12. - Steady-state effects of gas heat removal on fixed-power-system operating conditons. Ideal gas-thermal input, 27.5 kilowatts thermal; prime radiator area, 280 square feet; coolant mass-flow rate, 0.165 pound mass per second; working-gas inventory, 0.96 pound mass.

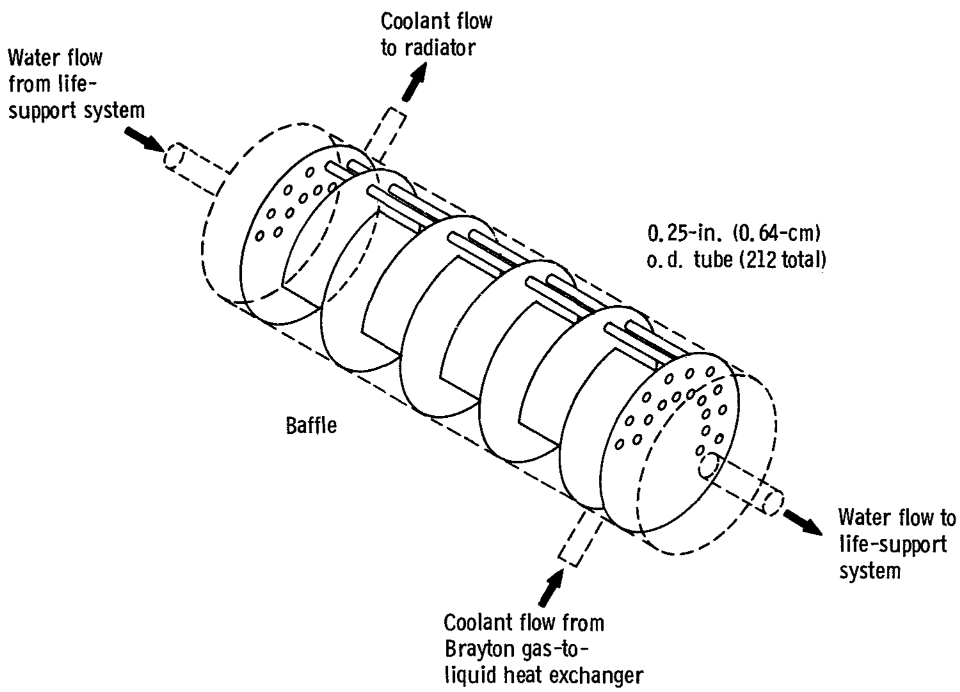


Figure 13. - Brayton - life-support-system interface heat-exchanger concept (liquid to liquid). Tube bundle: length, 19.5 inches; outside diameter, 5.5 inches; weight, 50 pounds; material, stainless steel; estimated heat transfer effectiveness, 0.7.

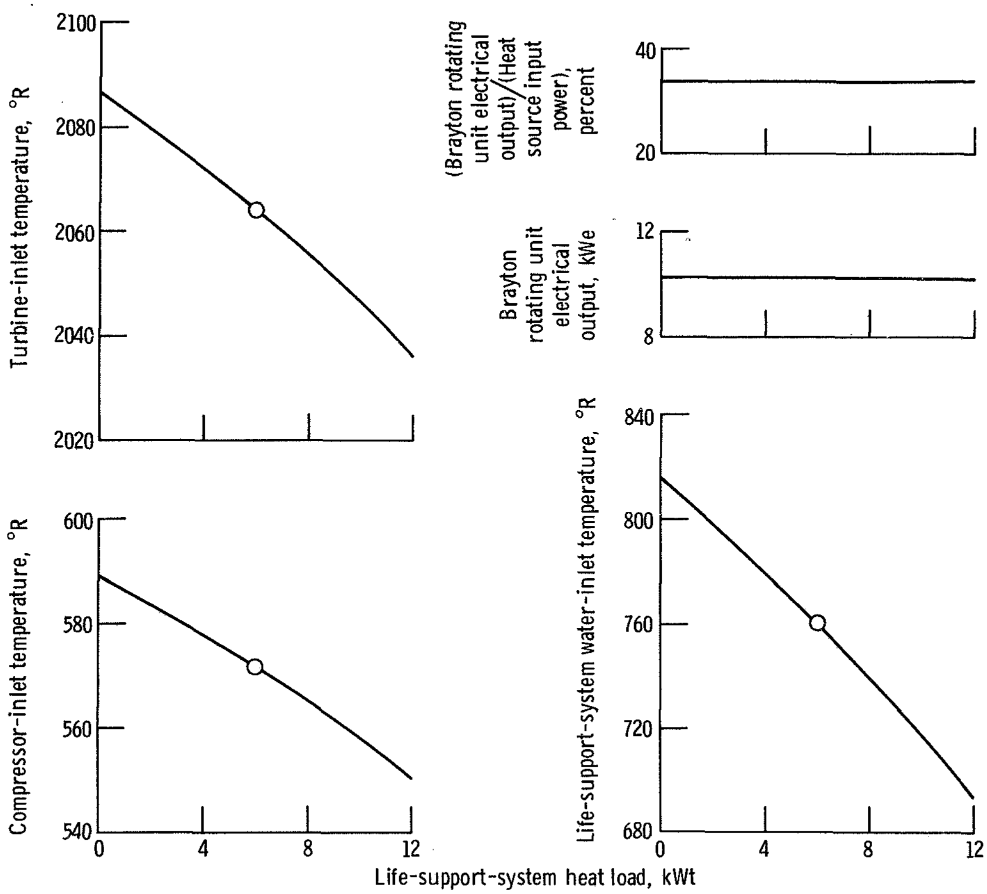


Figure 14. - Effects of life-support-system heat-load variation on water-inlet temperature, turbine-inlet temperature, and compressor-inlet temperature. Prime radiator area, 260 square feet; coolant mass-flow rate, 0.15 pound mass per second; source thermal input, 30 kilowatts; working gas, helium-xenon at molecular weight of 83.8; total gas mass, 1.035 pounds mass; water flow rate, 0.0833 pound mass per second.

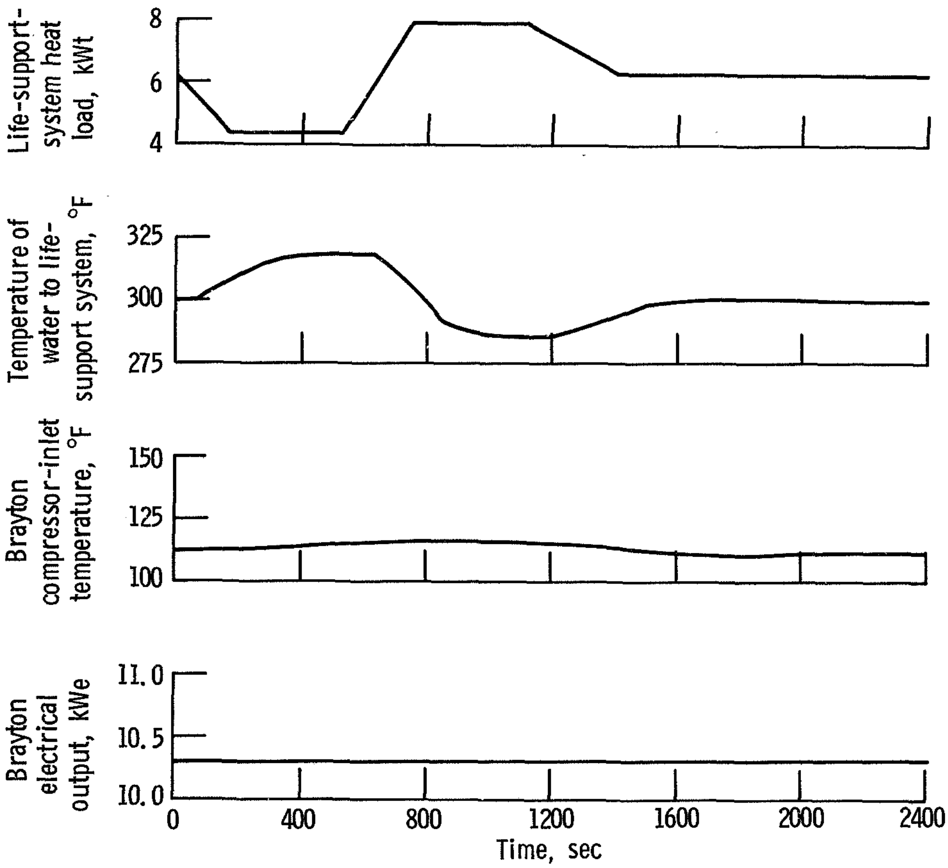


Figure 15. - One cycle of life-support-system process-heat load (typical).

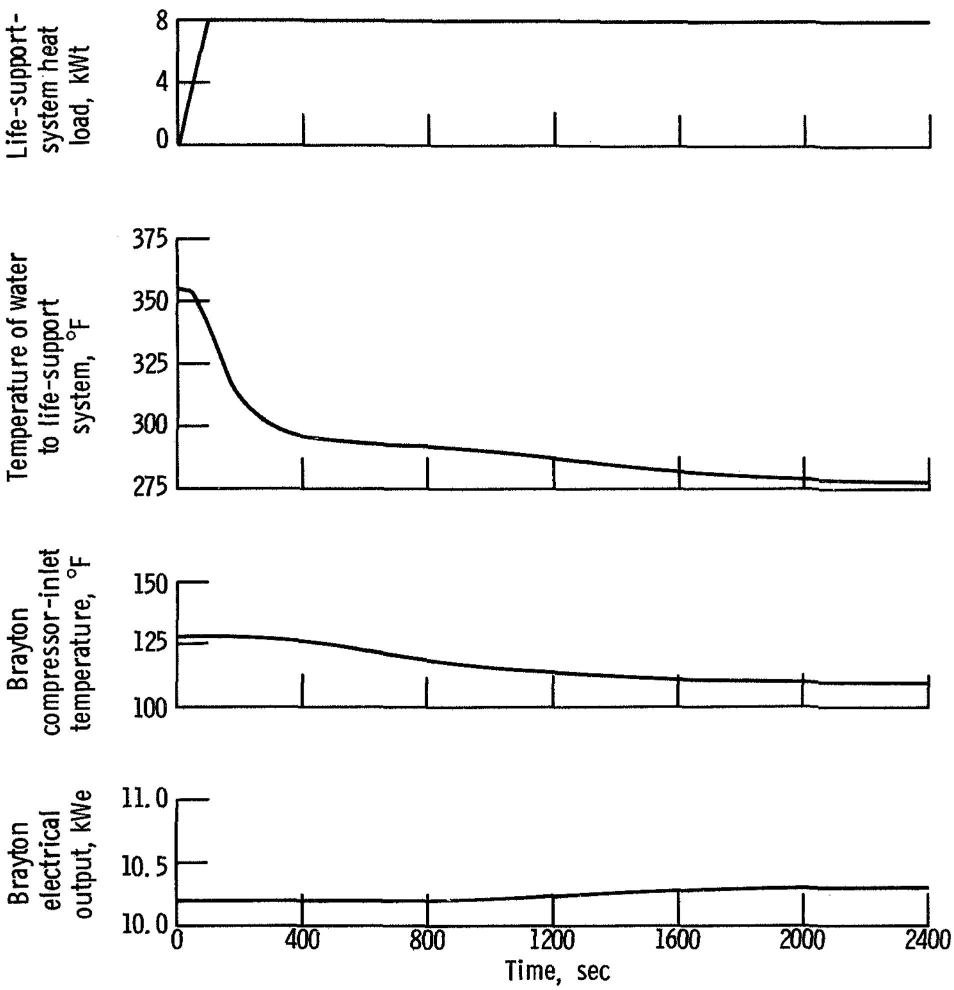


Figure 16. - Life-support system startup transient.